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Spacelabs, Inc.

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FINAL REPORT

BIO-GRID SYSTEM

PREPARED FOR:

NATIONAL AERONAUTICS AND
SPACE ADMINISTRATION
FLIGHT RESEARCH CENTER
EDWARDS, CALIFORNIA

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I SUMMARY

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Theoretical and experimental studies were conducted to indicate the feasibility of multiple bio-electrode arrays. Multiple sensor arrays picked up unanticipated large endosomatic galvanic skin response signal levels during body movement, appreciably distorting bio-potential signals at the frequency and amplitude spectrum equivalent to the electrocardiogram. Author

II SYNOPSIS OF TOTAL PROGRAM OBJECTIVES

Study and experimental programs were conducted to ascertain the effectiveness of a multiple contact electrode sensoring system. To determine the validity of this electrode concept, theoretical studies were conducted in electrode technology which considered the electrical resistance of the skin, metal-electrolyte interfaces, and the consequential effects of these determinations on the multiple sensing electrodes. Studies were then conducted to determine the resistance characteristics of this type of electrode. These studies allowed the overall signal attenuation of a bio-grid to be estimated.

Empirical experimentation was conducted to validify the results obtained by theoretical studies. Agreement between experimental results and theory was unfavorable for low resistance ranges, and for practical reasons the high resistance ranges could not be experimentally checked because the high electrode resistances were unobtainable in the multiple sensing mode. However, the empirical experiments indicated that for low resistive ranges less signal attenuation was achieved than the theoretical studies predicted. More important, the experiments indicated a much greater endosomatic response than was anticipated. This finding led to the consideration that the multiple sensing electrodes would be inherently susceptible to motion artifact relative to certain parameters such as ECG and EEG. Consequently, the latter stages of the program were redirected by NASA to emphasize the effects of body motion artifact. The results of this redirected emphasis indicated that low signal to noise ratios would be encountered in parameters such as ECG and EEG.

III SYNOPSIS OF LITERATURE SEARCH

During the early phases of the contract, a detailed literature search was made to explore other investigators' efforts with regard to multiple sensing electrodes. Certain works were uncovered pertaining to the multiple sensing electrode concept. The following paragraphs relate to the more important information obtained. P. Rijlant's paper, (Validation of a Dipolar Representation of Electrical Activity of the Heart) demonstrated experience with the concept of preparation of an isomorph of a homogeneous hyperbolic space to represent a human thorax. Characteristics of this space can be verified in measuring the resistance between all points to have an equal value. The significance of this paper lay by way of demonstrated experience for obtaining intelligence from the point source.

The paper by Ettleberg and Burch, "Physical and Chemical Surface Variables Influencing Skin Resistance and Galvanic Skin Response" was significant in that it alerted the investigators involved to the consideration that the galvanic skin response varied inversely with area of the electrode surface. The signal amplitude of the GSR's can be expected to be a very significant characteristic when sensed by multiple sensors over a large skin area.

It was hoped that more useful information relative to dipole electrodes existed in the literature than was actually found. Largely due to a lack of useful information and also as a result of some variances in the literature, a a requirement was indicated for a limited but detailed electrode study to define the state-of-the-art and to upgrade local experience. Descriptions of these experiments are given under the heading "Dipole Electrode Experiment".

IV HISTORY OF PROGRAM OBJECTIVES

The first program objective was to examine the electrical characteristics of the skin. This was accomplished by sub-contract to Teledyne Systems Corporation, Hawthorn, California. Detailed results of this investigation are given in their final report entitled "Electrical Resistance of the Skin".

The second objective was to establish electrode skin interface characteristics and this was accomplished by sub-contract to Autonetics, Research, Engineering and Reliability Division, North American Aviation. It is discussed in detail by their final report entitled "Theoretical Aspects of Metal-Electrolyte Interfaces".

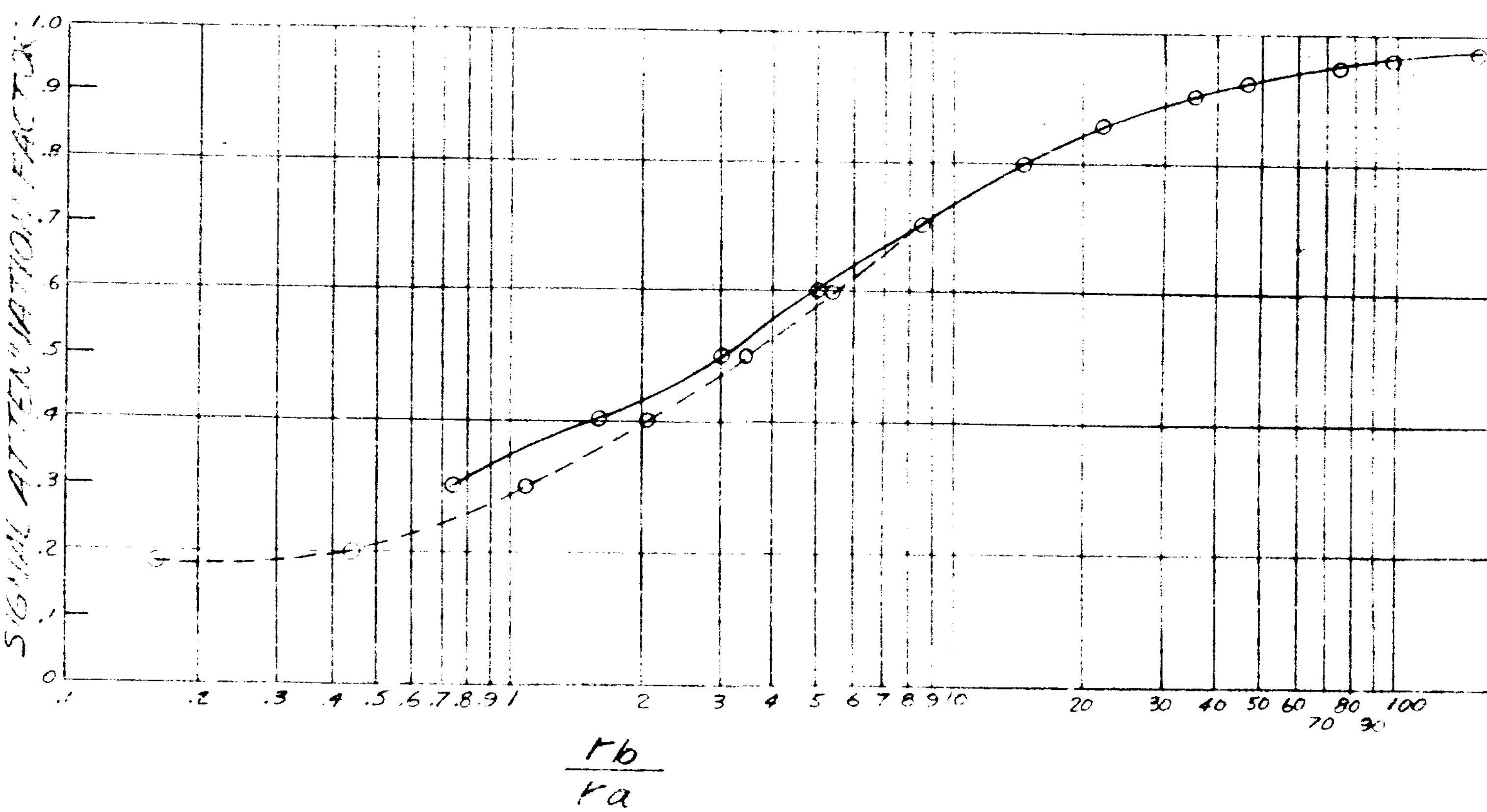
The third objective was to investigate the resistance characteristics of a multiple sensing electrode system and to integrate these results with the first two design objectives to provide an overall signal attenuation characteristic for a multiple sensing electrode array. These results are presented in detail by the Autonetics report by way of a finalized graph (Figure 1) giving signal attenuation versus various levels of skin resistance.

The fourth design objective of this program was to experiment empirically to determine the validity of the foregoing theoretical studies. This experimentation was accomplished by the prime contractor (Spacelabs, Inc.). These results indicated an unfavorable agreement between experiment and theory.

SIGNAL ATTENUATION FACTOR

VS

$$\frac{\text{BIO-GRID RESISTANCE}}{\text{SKIN RESISTANCE}}\ \text{RATIO}\ \left(\frac{r_b}{r_a}\right)$$



SOLID LINE- DATA FOR FIRST APPROXIMATION TO A MULTI-MESH BIO-GRID

DOTTED LINE- DATA FOR A FOUR-MESH BIOGRID

FIGURE 1

These results are discussed in greater detail under section entitled Electrode Experiments.

This experimental phase revealed an unanticipated large endosomatic response which raised considerations and concern leading to a redirected fifth program objective.

The fifth program objective was to investigate the effects of high signal level endosomatic response induced by body motion on signal levels similar in frequency content and amplitude to the ECG. Unfortunately, program funds were not available to determine experimentally the signal level of endosomatic response induced by body motion, but based on previous experimental data and additional studies, it is estimated that very low signal to noise ratios for ECG type signals would be characteristic with the type of multiple sensing electrode system being investigated.

V ELECTRODE EXPERIMENTS

A. Dipole Electrode Experiments

Dipole electrode studies and experiments were initiated early in the program to run parallel to the theoretical studies being conducted by Autonetics.

This effort in addition to being justified by the literature search was intended to provide a direct link between the theoretical and hardware aspects of dipole electrode technology.

Studies were initiated to determine some of the basic phenomena of polarization and self-generated electromotive forces and as a consequence of these studies the electrode material (silver, copper, silver-silver chloride, and stainless steel), together with several types of conductive paste were selected for experimentation. All materials were tested for impedance, polarization, and self-generated EMF, which was displayed on an oscilloscope. The displays were generated by the simultaneous observation of the current passing through and the voltage across two electrodes in close proximity of each other connected electrically by conductive electrode paste. The driving source was a sine wave oscillator. Simple measurements such as DC resistance, immediately becomes complex when one deals with solutions, paste, and metallic contacting materials. In order to minimize the effects of ionizing current, a special bridge circuit was designed in which the bridge current would be monitored and controlled. Impedance at various frequencies was calculated from measurements taken from oscillographs. Self-generated EMF was measured on a VTVM, HP 412A which is accurate to 1 millivolt full scale. Pairs of electrodes were measured in two modes: (1) electrode-electrode, (2) electrode-skin-electrode.

Test Procedure - In order to standardize the measurements made, fixtures were designed which held the electrodes a given distance apart and exposed a given area of each electrode. The exceptions in this procedure were the stainless steel mesh electrodes and Ag-AgCl electrodes from Spacelabs which had holes through them exposing to the electrolyte more than the single surface facing the other electrode. Electrode pastes formed a bridge between the two electrodes. The surface area was measured and current density controlled. The electrodes were connected to the oscillator and the current and voltage displayed on the oscilloscope.

Test Results - Self-generated voltages were easily read but not stable which agreed with the theoretical findings of Autonetics. The amount of electrode paste actually contacting the electrode surface was a large factor in the measurement. The EMF could be read to within 1 mv. The lead material and lead junction material were also large factors in EMF because the two dissimilar metals formed a battery in the paste solutions. In this respect, the AC impedance readings were not troublesome.

The electrode impedance as tested in the Electrode-Electrode configuration fell in the 1K to 10K ohm range at 0.01 cps and the 6 to 10 ohm range at 100 KC. Other values between these extremes form an almost linear plot on log-log paper. See Figure 2. The exception in this group was the silver-silver chloride electrode which displayed an impedance of only 40 ohms at 0.01 cps and 10 ohms at 100 KC. The impedance curves of the Ag-AlCl electrode joined the other impedance curves at 100 cps and from there to 100 KC the impedances were very similar.

The self-produced EMF varied from 8 to 100 mv over the array of several electrode materials with the exception of the Ag-AgCl electrodes which commonly fell below the 1 mv reading. After cycling at the low frequency of 0.01 cps at 1 ma the EMF was usually increased.

In the testing of various pastes, the electrode was again the Ag-AgCl electrode. Here, the impedances of the pastes were very similar and fell into a range of 40 - 100 ohms at 0.01 and 6 to 10 ohms at 100 KC. The newly plated electrodes were used for the several pastes in succession without re-plating and the resulting impedances were progressively higher. The pastes used were Natrasol, Burdick, Redux, and Offner, in that order.

B. Electrode - Skin - Electrode Mode

Test Procedure - The site selected for the Electrode-Skin-Electrode test was the forearm and two areas five cm apart. The site was thoroughly washed with alcohol. Electrode paste was rubbed into the two areas with an eraser. The electrodes were fastened to the skin with Stomoseal. Electrode paste made contact to the skin. Again, the electrodes were connected to the oscillator and oscilloscope and impedance measurements taken. The

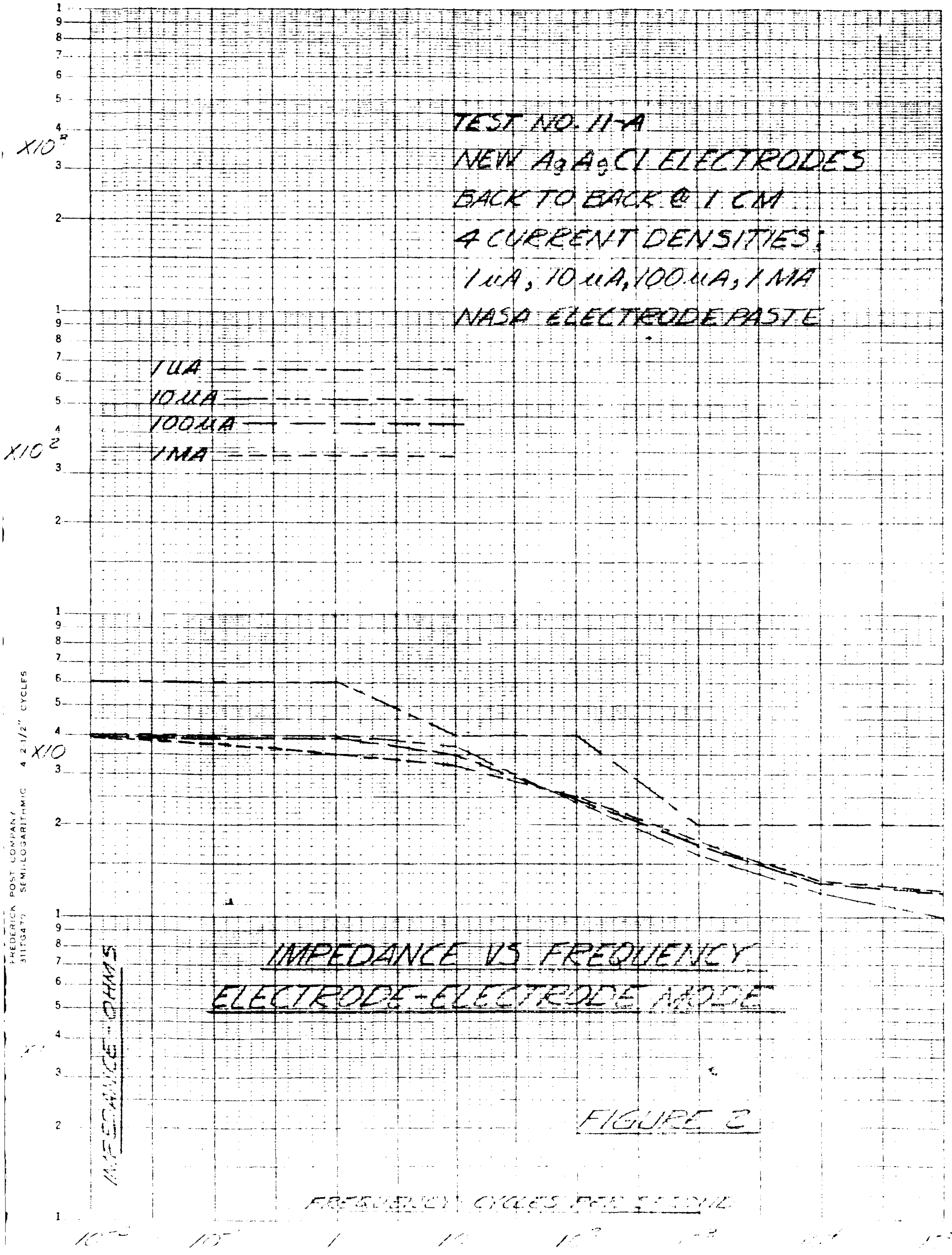

TEST NO-11-A
NEW Ag AgCl ELECTRODES
BACK TO BACK @ 1 CM
4 CURRENT DENSITIES:
1uA, 10uA, 100uA, 1 MA
NASA ELECTRODE PASTE
1UA
10UA
100UA
1MA
X10^3
X10^2
X10
IMPEDANCE - OHMS
IMPEDANCE VS FREQUENCY
FREDERICK POST COMPANY
SEMI-LOGARITHMIC 4 2-1/2" CYCLES

FIGURE 2

self-generated EMF and DC resistance were also measured as before.

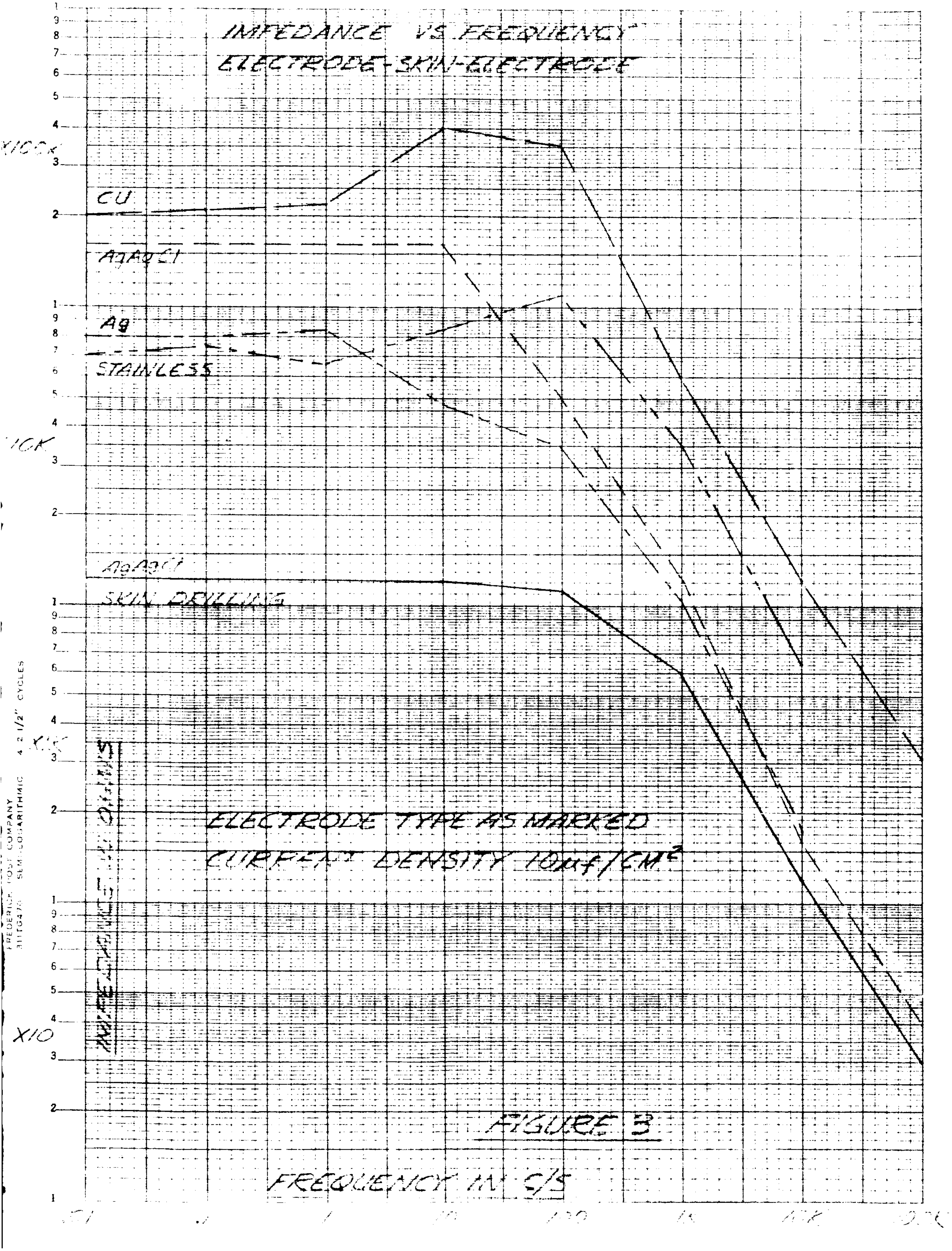
Test Results - Electrode-Skin-Electrode impedance show a very uniform impedance over the 0.01 cps to 10 cps range. Above 10 cps the decrease in impedance is at the same rate as for the electrodes in the Electrode-Electrode configuration. See Figure 3. The impedances cf the various electrodes at 0.01 cps to 10 cps ranged from 70 K ohm to 500 K ohm and at 100 Kc, 400 to 3.2K ohm. The Ag-AgCl electrodes fell into median values of these presented.

Added to the many variables of skin condition and states are the variables of electrode materials and their surface condition. Also, with the Ag-AgCl electrodes the plating time and current density are very significant in the overall impedance and wearing properties.

C. Bio-Grid Experiments

As indicated in the Teledyne Systems Corp. subcontract report, "Electrical Resistance of the Skin", the body may be represented as a resistive grid network. From the dipole source; i.e., the heart, and through body tissue, the mesh resistance is rather low. However, the skin resistance mesh is rather high and somewhat variable. It is this matching the resistance of an external bio-grid to the network resistance of the skin over a very large area which should provide artifact free connection to sense bio-potentials.

Referring to the derivation of a multi-mesh bio-grid in the report, the relationship between signal attenuation factor and



IMPEDANCE VS FREQUENCY
ELECTRODE-SKIN-ELECTRODE
X100K
CU
AgAgCl
Ag
STAINLESS
10K
AgAgCl
SKIN DRILLING
X1K
IMPEDANCE IN OHMS
ELECTRODE TYPE AS MARKED
CURRENT DENSITY 10µf/CM²
X10
FREQUENCY IN C/S
.01
.1
1
10
100
1K
10K
100K
FREDERICK POST COMPANY
311TG470 SEMI-LOGARITHMIC 4 2 1/2" CYCLES

FIGURE 3

$\frac{r_b}{r_a}$ Ratio, where r_b = Mesh resistance between corners of a grid and r_a = skin resistance per square, it is noted that bio-potential attenuation is a consideration in the design of a bio-grid system. However, only 6 db attenuation is shown for a $\frac{r_b}{r_a}$ = 3.0 and 10db for $\frac{r_b}{r_a}$ = 1.0.

Assuming a skin resistance of 20,000 ohm/square and a bio-grid of 20,000 ohm/square we may expect an ECG signal of about 0.9 MV. This is a substantial signal and, most important, appears to the signal conditioner as a very low impedance source, in this case 20KZ. However, this ECG signal level is valid only if other bio-potentials of the same frequency range are not of the same approximate signal level. To indicate the effect of other bio-potentials a series of experiments were designed to investigate the signal levels of all bio-potentials in the ECG amplitude range.

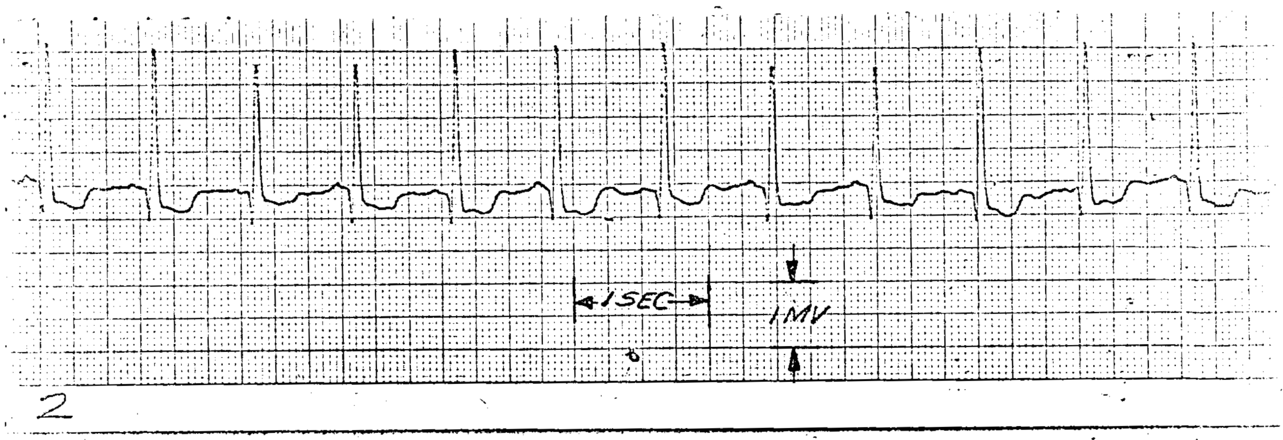
The stimulus provided by the Teledyne report, "Resistance of the Bio-grid", led to a simulation study of the electrocardiogram to ascertain rapidly and easily the validity of the bio-grid concept.

Test Procedure - The electrocardiographic potentials of the subject were recorded on a Sanborn Recorder utilizing Spacelabs' electrodes applied between the sternum and left leg, across the chest and with other electrode configurations. Then the subject was immersed below the level of the neck in tap water, a liquid conductive medium. A pair of electrode probes were situated 1/2 inch away from the skin in configuration similar to those previously described and bio-potentials recorded.

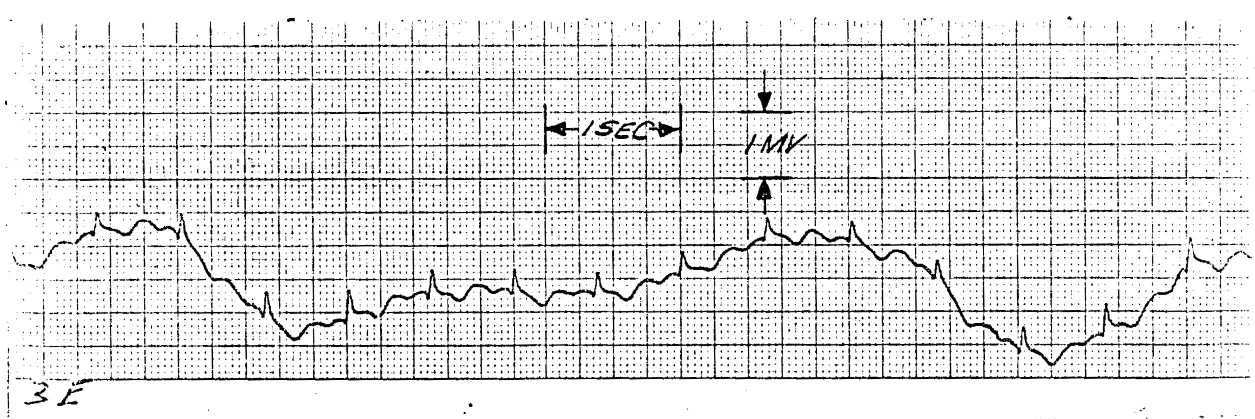
Test Results - The electrocardiogram recorded prior to immersion between sternum and leg is shown in Figure 4A. Endosomatic GSR potentials were demonstrated from several leg configurations as shown in Figure 5A. Electrode impedances were determined under these conditions by impedance matching the source and load to the half amplitude point. Source impedances of 15 to 20,000 ohms were found. After immersion, using the probe electrodes, the recordings show an attenuation of the ECG amplitudes. This attenuation ratio is approximately 1 to 5 as demonstrated by comparison of Figures 4B and 5B. Large endosomatic GSR was found to accompany respiration as illustrated in Figure 6.

The source impedance during immersion was determined by the method previously described and found to be 1500 ohms. No measurements were made at higher mesh resistances because of lack of deionized water. Assuming the 1500 ohms impedance to be a measure of the bio-grid mesh resistance (^{r}b) and the pre-immersion impedance to be similarly related to the skin resistance (^{r}a), the attenuation ratio of the ECG was compared to the results found in the Teledyne report, Figure 1 and found to be within an order of magnitude or less of the predicted attenuation. However, as shown by the large endosomatic GSR, any motion artifact in the ECG frequency range would completely obscure the ECG bio-potential.

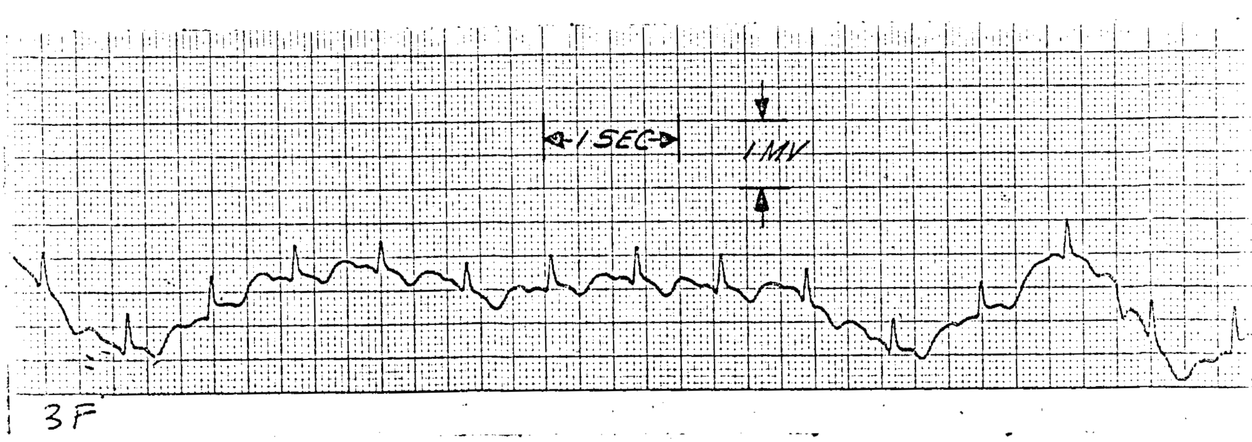
Figure 4 Effect of Tap Water Immersion on ECG Amplitude.



A. Subject not immersed. Spacelabs Electrodes.
Location - Sternum and Leg.

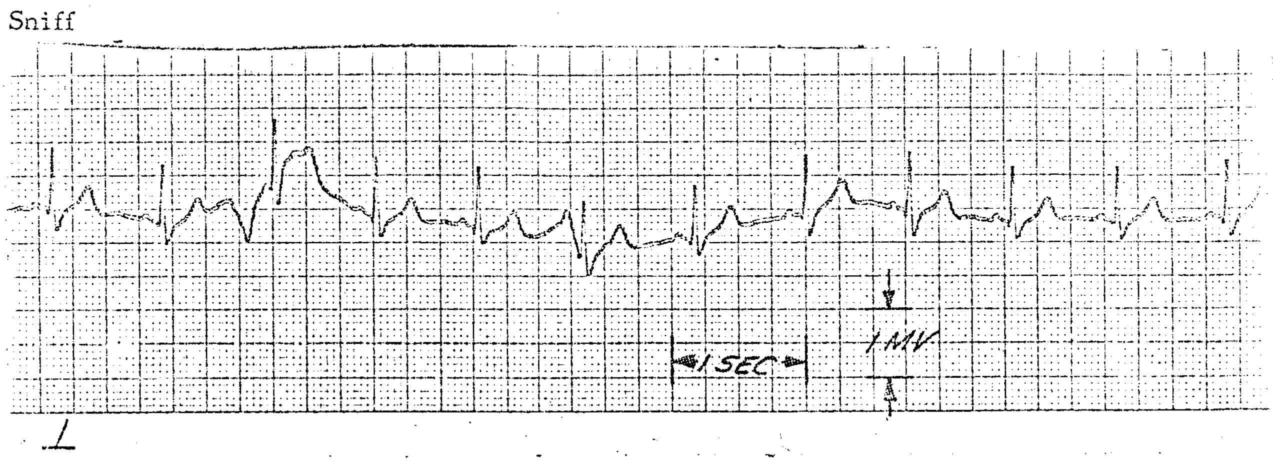


B. Subject Immersed in Tap Water. Probe Electrodes.
Location - Over Sternum and Leg, as in A.

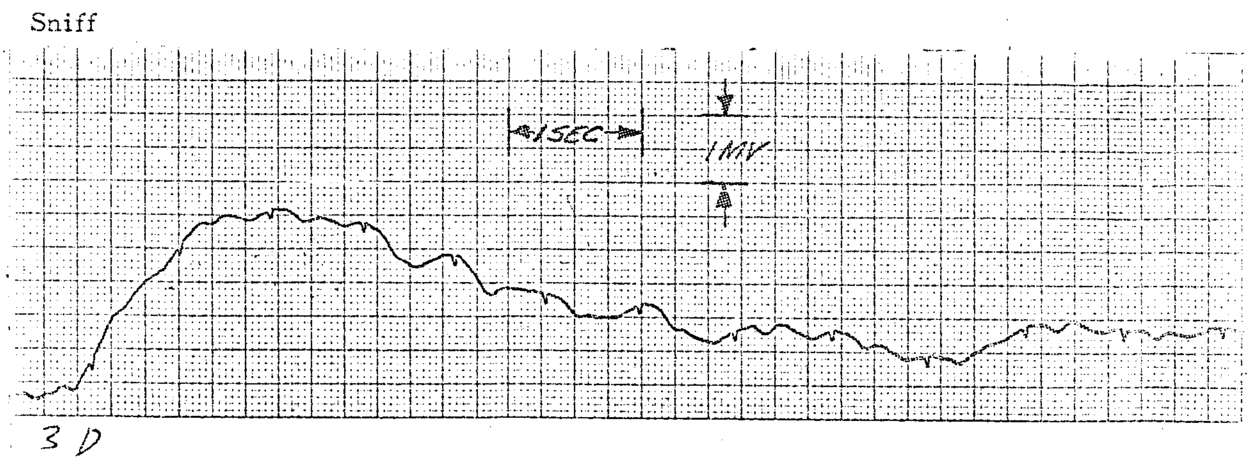


C. Subject Immersed in Tap Water. Probe Electrodes.
Location - Dorsal Neck - Leg.

Figure 5 Effects of Immersion in Endosomatic GSR.

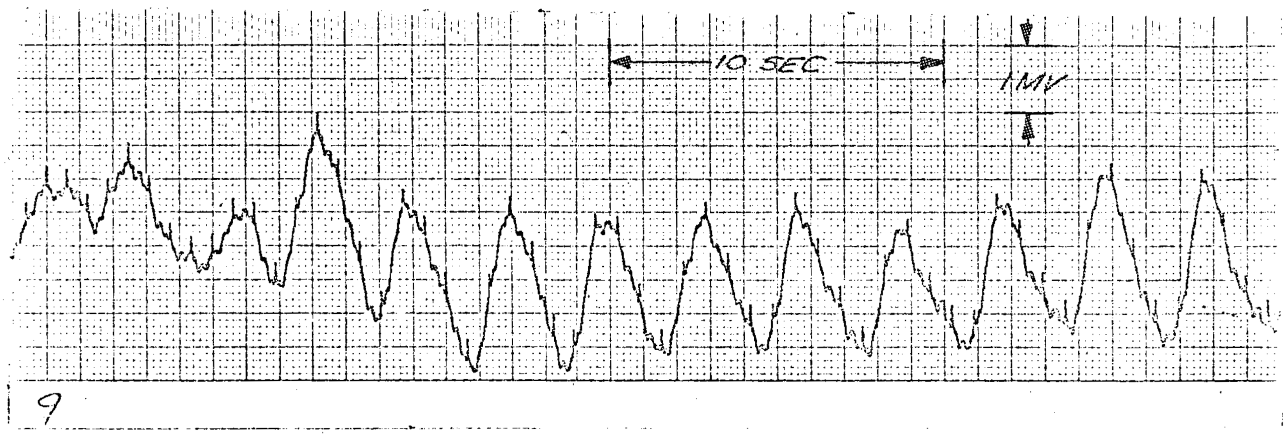


A. Subject not Immersed. Spacelabs Electrodes.
Location - Lateral Chest Wall



B. Subject Immersed in Tap Water. Probe Electrodes Located 1"
away from Lateral Chest Wall.

Figure 6 Immersion Augmentation of Endosomatic GSR Associated with Respiration.



Subject Immersed. Probe Electrodes at Dorsal Neck and Leg.

VI DESIGN CRITERIA

Resistivity per square of a practical bio-grid is defined by skin resistance and by acceptable attenuation of the bio-potential signal.

Required, is a substance which has capability of conforming to a human thorax, be non-toxic, durable, meet the requirements of electrodes and to have a homogeneous conductivity falling into the range defined in the experiments. A search was made for suitable materials from which a bio-grid assembly could be made. A material produced by Insulating Materials Div., General Electric Co., shows the best promise in our search. It is an irradiated polyolifin film, having a resistivity of about 500 ohm-cm, is thin and conformable. Skin reaction and bio-potential electrode function of this material have not been examined. Electrode connections would be made by bonding techniques to the exterior surface of the formed film. A suitable signal conditioner may have a relatively low input impedance, matching the resistance per square of the bio-grid. The low source impedance to the signal conditioner has inherently lower noise factors and reduces electrostatic field pickup.

VII CONCLUSIONS

These experimental data have indicated that the feasibility of using multiple sensing arrays over large skin areas is questionable for detecting point source potential differences from such organs as the heart.

However, the large signal levels generated by endosomatic response as a consequence of respiratory motion is extremely indicative of the possibility of using this bio-potential sensor technique for gaining knowledge in the realm of galvanic skin response. The program scope of this contract did not allow further investigations into this very interesting aspect.

REPORT REFERENCES

The Validation of a Dipolar Representation of the Electrical Activity of the Heart

P. Rijlant - Institut Solvay de Physiologie, University of Brussels

Technical Information Office
European Office Aerospace Research
Shell Bldg., 47 Cantersteen
Brussels, Belgium

Physical and Chemical Surface Variables Influencing Skin Resistance and Galvanic Skin Response

Robert Edelberg and Neil R. Burch

Department of Psychiatry
Baylor University College of Medicine
and
Houston State Psychiatric Institute
Houston, Texas

Theoretical Aspects of Metal-Electrolyte Interfaces

Final Report #C4-1472/3111
Subcontract 6625
Prime Contract NAS-4-566
14 September 1964

Autonetics
A Division of North American Aviation, Inc.
Anaheim, California

Electrical Resistance of the Skin

Subcontract 6666
Prime Contract NAS4-566
2 November 1964

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Resistance of the Biogrid

Subcontract 6666
Prime Contract NAS4-566
4 January 1965

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